CHANGING CONTRIBUTIONS OF SUSPENDED SEDIMENT SOURCES IN SMALL BASINS RESULTING FROM EUROPEAN SETTLEMENT ON THE CANADIAN PRAIRIES

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ABSTRACT

Lake sediments provide an integrated record of the sediment yields and sources in the contributing basin. In the research area on the prairies of western Canada, the earliest sediments deposited in the larger lakes predate European settlement, allowing direct evaluation of basin response to settlement. Lake sediment cores were collected from an unnamed lake in the Stony Creek drainage basin in the aspen parkland region of eastern Saskatchewan. Pre- and post-settlement sediments in a central core were separated on the basis of an increase in *Populus* pollen associated with the southward advance of the aspen parkland ecotone caused by fire suppression following settlement. A wet chemical extraction procedure was used to separate the operationally defined organic fraction, the acid-soluble authigenic fraction, and biogenic silica from the clastic, non-carbonate, allogenic fraction of the lake sediment. Changes in the mineralogy and geochemistry of the clastic, allogenic fraction indicate that settlement resulted in an increased contribution of topsoil to the sediment load of Stony Creek. Elemental ratios, however, show that topsoil did contribute to the allogenic lake sediment fraction prior to settlement. Post-settlement changes in deposition rates of the allogenic fraction resulted from changes in land use rather than from climatic variability. Allogenic deposition rates reached a maximum in the 1950s and 1960s owing to an increase in the area under field crops and the increased use of high-powered agricultural machinery. Allogenic deposition rates decreased in more recent years because of a more extensive application of soil conservation measures. Post-settlement changes in deposition rates of individual elements within the allogenic fraction indicate that various sediment sources respond differently to changes in land use. Over the most recent 100 years, since the onset of European settlement, the erosional response of the basin appears to be controlled by land use changes rather than by climatic variability.

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INTRODUCTION

Background

One of the most challenging problems in geomorphology is the prediction of landscape response to environmental change. Environmental change can have pronounced geomorphological effects as shown, for instance, by the examples presented in Goudie (1992). Relatively little, however, is known about the dynamics of landscape response to environmental change. This study forms part of a larger project aimed at predicting the effect of environmental change on the erosional response of drainage basins on the Canadian prairies, specifically in terms of sediment quantity and quality. The Canadian prairie region was selected for this study as an example of an area where, in addition to geomorphological effects, environmental change will have a direct social and economic impact. The successful growth of crops in this productive region critically depends on climatic factors such as the length of the growing and frost-free seasons, and the occurrence of precipitation. In addition, this region is the location of the boundaries between the long- and short-grass prairies, the aspen parkland and the boreal forest. The location of each vegetational boundary is determined by climatological conditions and can respond to changes in climate, as indeed has occurred in the past (e.g. Ritchie, 1976).

Projected changes over the next 50 to 100 years are significant because this period lies within the scope of current policy initiatives and planning strategies relating to water resources, economy and other practical

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issues. The time scale is crucial in determining the scope of this study in that to have any practical implications the information on basin response to environmental change should be highly detailed. To obtain the best possible information the research project was designed to consist of process observations of the suspended sediment dynamics of a drainage basin contributing sediment and water to a lake, combined with a study of the recent (100–150 years) lake sediment record. The direct benefits of this approach are twofold: first, contemporary process data allow the most recent lake sediment to be evaluated in terms of contemporary sources and yields; and second, the lake sediment record allows modern data to be extrapolated to the recent historical past. Thus, the time scale of the process observations is effectively extended, thereby avoiding two of the main pitfalls in extrapolating contemporary process data. The first of these pitfalls is that the time series characterizing geomorphic processes rarely extend for more than a few years. Such an observation period is unlikely to provide respresentative data even for current conditions, simply because the observation period is too short to adequately characterize the temporal behaviour of the geomorphic system of interest (Church, 1980). A second, further complication is that geomorphic systems generally do not respond immediately to changes in the driving variables such as land use or climate. Instead, geomorphic systems are characterized by a reaction time, which represents the time-lag between a disturbance, or a change in driving variables, and the response of the geomorphic system.

The approach used in the present study is based on that of Foster *et al*. (1985) who used a combined study of lake sediments and contemporary sediment dynamics to obtain and compare long- and short-term estimates of sediment yield. The present study focuses on sediment characteristics. At present, topsoil is the dominant suspended sediment source in small drainage basins in the field area. The objective of the part of this study reported in the present paper was to investigate whether this has always been the case or whether European settlement in the region resulted in a shift in dominant suspended sediment source from stream banks to topsoil. Such a change in the topsoil contribution and suspended sediment characteristics would imply a significant change in the physical, chemical and biological characteristics of the aquatic ecosystem. It is worth noting that even though it would be expected that European settlement and the introduction of agriculture would result in an increased topsoil contribution, this has not occurred in some regions (e.g. Engstrom *et al*., 1985).

The lake sediment record

Lake sediment characteristics reflect the combined effect of a large variety of processes operating on the slopes of the contributing basin, in the sediment delivery system, in the lake water, and in the sediment after deposition. A number of studies have used the lake sediment record to evaluate the erosional history of the basin contributing water and sediment to the lake. Recent reviews of this approach have been published by Oldfield and Clark (1990) and Dearing (1991). Mackereth (1966) carried out one of the earliest investigations into the chemical stratigraphy of lake sediments, and used Na, K and Mg profiles as indicators of weathering and erosion intensity in the English Lake District. Since then, lake sediment chemistry has been used by a number of investigators to deduce the erosional history of the contributing basin. Early studies of lake sediment chemistry, however, were almost all based on bulk chemical analysis, even though lake sediment chemistry is controlled by processes in the water column and within the deposited sediment, in addition to the processes operating on the slopes and in the streams of the contributing basin.

To overcome the limitations posed by the bulk analysis method, Engstrom and Wright (1984) devised a fractionation procedure based on wet chemical extraction to separate the lake sediment into fractions according to origin. Engstrom and Wright (1984) distinguished the allogenic, authigenic and biogenic fractions: the allogenic fraction refers to the component derived from outside the lake; the authigenic fraction describes the component formed as a result of processes within the lake, either in the water column or in the sediment after deposition; and the biogenic fraction refers to the amorphous silica content which is primarily composed of diatom frustules. Note that the various fractions are operationally defined because the separation of the various fractions, which is intended to be based on sediment origin, is to some extent affected by the operational procedures. The fractionation procedure described by Engstrom and Wright (1984) has been used in various other studies, sometimes in slightly modified form (Engstrom and Hansen, 1985; Engstrom and Swain, 1986; Engstrom *et al*., 1985; Heathwaite and O’Sullivan, 1991; Foster and Walling, 1994). The present study uses the fractionation procedure of Engstrom and Wright (1984) to evaluate the changing properties of the allogenic

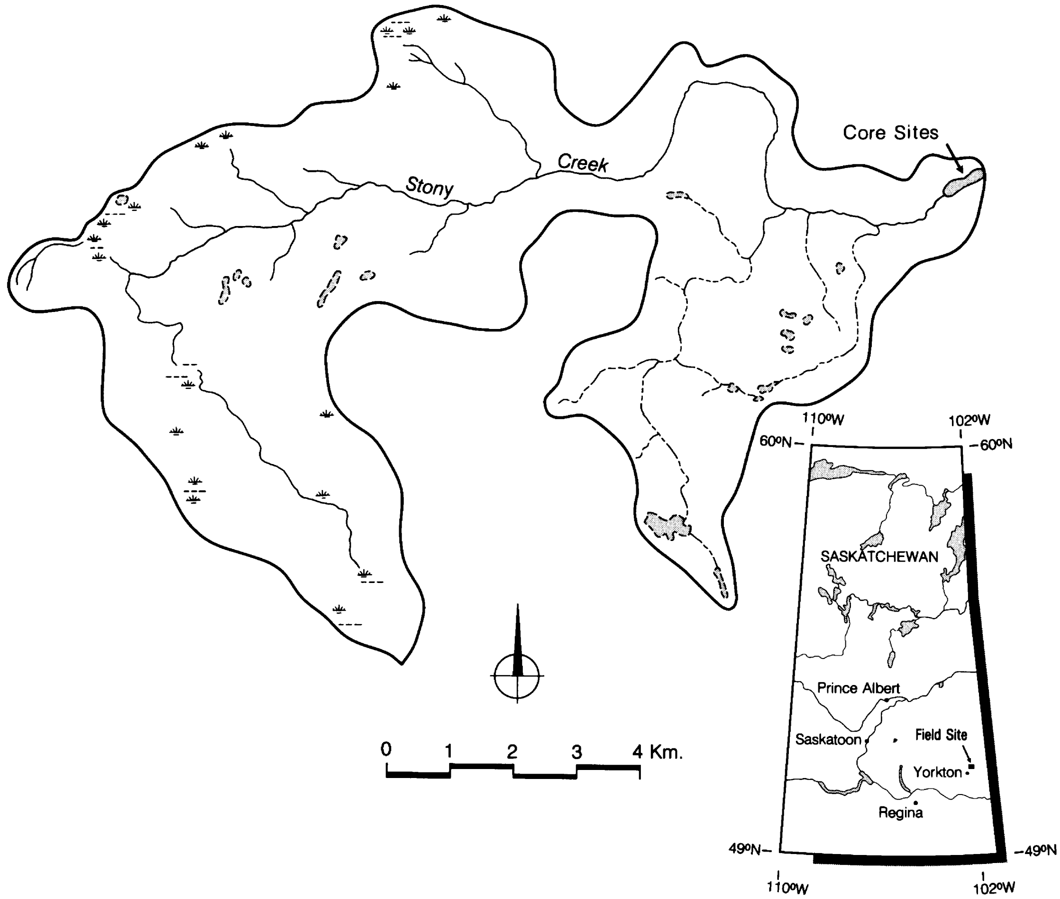

Figure 1. Location of Stony Creek drainage basin in Saskatchewan, Canada

fraction resulting from settlement and subsequent changes in land use in a small, agricultural basin on the Canadian prairies.

STUDY SITE

The area selected for this study is located in the aspen parkland region of eastern Saskatchewan, Canada (Figure 1). The climate in the field area is humid continental or Dfb in the Köppen climate system (Ahrens, 1991). Kamsack, located 10 km north of the Stony Creek basin, has an average annual temperature of 0·9°C and an average annual precipitation of 386 mm with a summer maximum (Atmospheric Environment Service, 1982). On average, 26 per cent of the annual precipitation falls as snow.

Lake sediment cores were obtained from an unnamed lake, approximately 1 km long and 100 m wide, with a gross drainage area of 72 km^2. The lake is located in the Stony Creek basin, an agricultural catchment with a total gross drainage area of 461 km^2 at Environment Canada hydrometric station 05MD010 (Stony Creek, near Kamsack) further downstream. The topography of the area is irregular and hummocky, with numerous closed depressions. As a result, the effective drainage area of Stony Creek at the Environment Canada hydrometric station is only 116 km^2, or 25 per cent of the gross drainage area. Even though the effective drainage area of the lake cannot be unequivocally determined, it is probably a similar percentage of its gross drainage area. The lake is extremely shallow, and the greatest water depth observed during coring was 1 m.

Surface deposits in the area are primarily till and glacial outwash, with colluvium and alluvium occurring directly adjacent to Stony Creek. Soils in the basin are medium- and coarse-textured black soils (chernozemic

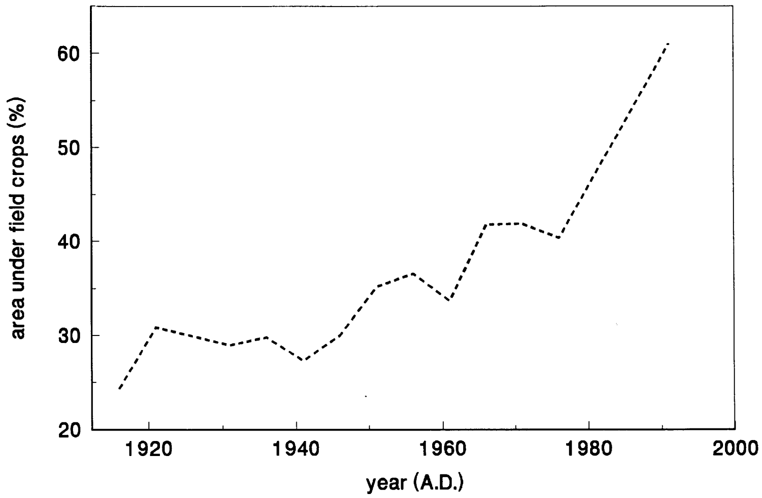

Figure 2. Area under field crops in the Calder, Wallace and Coté rural municipalities

order, Oxbow, Yorkton and Whitesand Associations, typically formed under grassland), degraded black (transition) soils (Whitewood Association), and medium-textured, upland, grey soils (luvisolic order, Waitville Association, typically formed under forest) (Mitchell *et al.*, 1977). Soils on the steep slopes adjacent to Stony Creek are classified as eroded, with a varied texture and thin, truncated profiles (Mitchell *et al.*, 1977).

Land use history and vegetational change

Agricultural settlement in the region started in the 1880s with the establishment of the first homesteads in the area (Anonymous, 1967). In 1903 the Canadian Northern Railway expanded into the region, leading to an increased influx of settlers, and by 1905 the area was 'well settled' (Anonymous, 1967). Figure 2 shows the change in the percentage of area under field crops during the period 1920–1991 in the three rural municipalities (Calder, Wallace and Coté) in which the Stony Creek basin is located. In this century there were four periods when the area under field crops sharply increased: (1) during initial European settlement up until 1921; (2) from 1941 to 1956, during and immediately after World War II; (3) from 1961 to 1966; and (4) from 1976 to 1991, the most recent year for which land use data are available. The percentage of area under field crops reflects the availability of mechanized farm equipment and the complex interplay of grain prices and farm subsidies.

At present, the study site lies within the aspen parkland ecotone (Archibold and Wilson, 1980) which is the transition between the grasslands of the Great Plains and the boreal forest. The aspen parkland typically consists of groves of aspen (*Populus tremuloides*) in the wetter locations in the landscape such as hollows and north-facing slopes, combined with grassland (fescue prairie) on the drier ridges and south-facing slopes. In the recent past, the vegetation of the area has changed in response to changing land use practices. Most authors report an expansion of aspen groves and replacement of grassland by aspen parkland since agricultural settlement as a result of fire suppression (Archibold and Wilson, 1980; Thorpe, 1993). Bird (1961) presented maps of the extent of the aspen parkland in 1905 and 1956, which show the expansion of the aspen parkland southward.

METHODS

Coring

Lake sediment cores were collected in February 1992 from the ice cover. Twenty-one cores were taken along two parallel transects running the length of the lake. Cores were spaced 100 m apart in the upstream part of the lake, and 50 m apart in the downstream part of the lake. The coring device used was a modified version of the Reasoner (1986) lightweight percussion corer, and collects a 3 inch diameter core in a PVC tube.

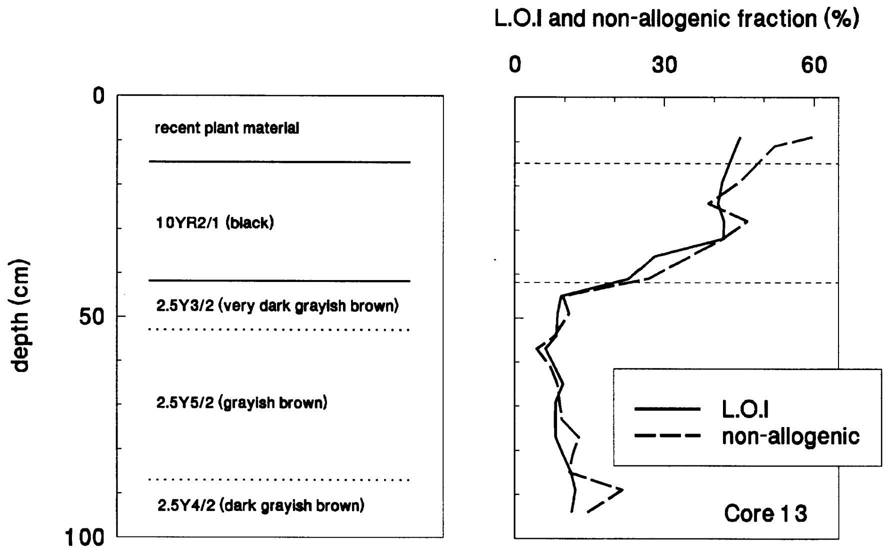

Figure 3. Lake sediment stratigraphy, loss on ignition (LOI), and the percentage of non-allogenic sediment of Stony Creek Core 13

Laboratory analyses

In the laboratory the cores were split lengthwise for visual inspection of the sediment structure. Directly after splitting, the colour of the moist sediment was described using Munsell Soil Color Charts, and the cores were sectioned into 1 cm slices which were used for further analysis. Core 13 was selected for further detailed analysis because of its central location in the deepest part of the lake and the absence of visible gaps in sediment deposition. Core 13 had an overall length of 95 cm. Loss on ignition (LOI) at 550°C was determined using standard methods (e.g. Lim and Jackson, 1982). Subsamples from selected depths were prepared for pollen analysis using standard methods (e.g. Faegri and Iversen, 1975). For each subsample, approximately 300 pollen grains were counted. A wet chemical extraction procedure, as described by Engstrom and Wright (1984), was used to separate the operationally defined allogenic, authigenic and biogenic fractions. The extracts were analysed by inductively coupled plasma (ICP) spectrometry. After the wet extraction sequence, the remaining residue underwent a multi-acid digestion ($HF/HNO_3/HC10_4$) prior to analysis by ICP spectrometry. Cs-137 and Pb-210 were measured by low-background gamma spectroscopy using a system similar to that described by Appleby *et al*. (1986) modified to provide a larger detector size and well volume. Low frequency magnetic susceptibility was measured with a Bartington magnetic susceptibility bridge.

RESULTS

Sediment colour and LOI

Based on sediment colour, the lower, mineral part of core 13 consists of two strikingly different layers. From 15 to 42 cm the sediment is black (10YR2/1), changing gradually to very dark grey (10YR3/1) at the bottom of the layer. A sharp boundary at 42 cm separates this material from the underlying greyish brown sediment, which can be further subdivided on the basis of slight differences in colour (Figure 3). The change in colour coincides with a sharp change in LOI, which varies over a depth of about 5 cm from values in excess of 40 per cent in the upper, black layer, to values of less than 10 per cent in the lower, lighter coloured material (Figure 3). LOI values correspond closely to percentages of non-allogenic sediment, defined as the percentage of lake sediment dissolved during wet chemical extraction.

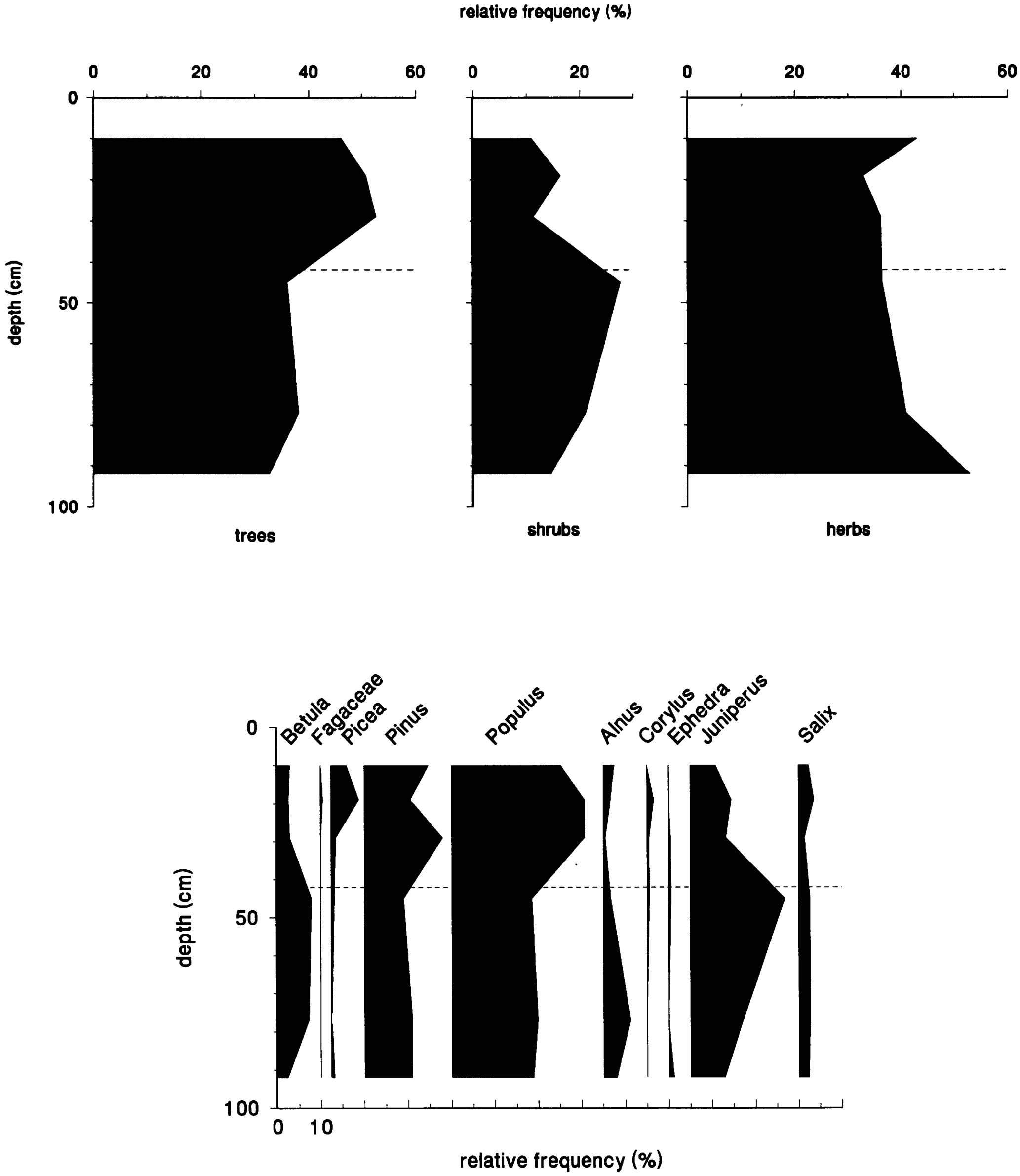

Figure 4. Pollen profiles of Stony Creek Core 13. Dashed line at 42 cm indicates boundary between black and greyish brown sediment

Palynology

Pollen analysis was used as a dating tool, and samples from various depths were selected to establish whether changes in sediment geochemistry corresponded to palynological changes. The relative frequencies on all pollen diagrams were calculated as percentages of total terrestrial pollen. The pollen diagrams show a marked increase in the percentage of tree pollen, from 36 per cent at 45 cm to 52·7 per cent at 29 cm (Figure 4). A breakdown into individual species shows that the increase in tree pollen is mainly due to *Populus* sp. (aspen), with concurrent increases in *Picea* sp. (spruce) and *Pinus* sp. (pine). The latter two species, however, are unlikely to be local. The increase in tree pollen is almost entirely at the expense of shrub pollen, especially *Juniperus* sp. (juniper). The percentage of herb pollen remains relatively constant throughout the core (Figure 4).

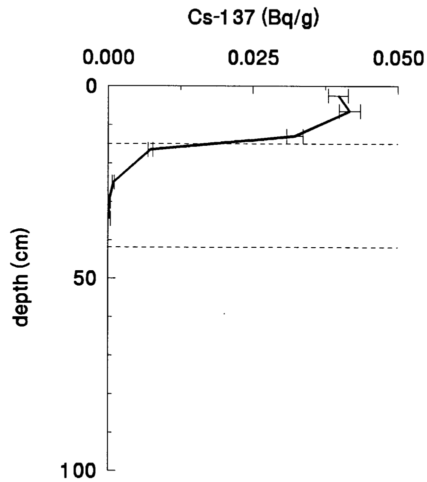

Figure 5. Cs-137 profile of Stony Creek Core 13. Error bars indicate standard deviation. For Core 13, dashed lines at 15 and 42 cm, in this and in Figures 6–8, indicate the boundary between the recent plant material and the black sediment (upper dashed line) and the boundary between the black sediment and the greyish brown sediment (lower dashed line)

Cs-137 and Pb-210

Cs-137 is a by-product of atmospheric testing of nuclear bombs in the 1950s and 1960s. It reaches the Earth's surface as fallout, where it becomes rapidly and, under oxidizing conditions, irreversibly adsorbed to the clay fraction of the topsoil. Once adsorbed, further Cs-137 transport can only occur in association with the clay fraction, making Cs-137 highly suitable as a tracer for topsoil transport (see Ritchie and McHenry (1990) for a comprehensive review). In general, measurable amounts of fallout Cs-137 were found starting in 1954. On the Canadian prairies approximately 60 per cent of the fallout occurred from 1962 to 1964, with 1963 being the peak year (De Jong *et al*., 1982; Kiss *et al*., 1988). The Cs-137 profile shows an increase in Cs-137 activity between 17 and 25 cm and a peak at 7 cm (Figure 5).

Unsupported Pb-210 decreased sharply below 17 cm, providing a Pb-210 date of 1865 calculated with the CRS model (Appleby and Oldfield, 1978) for this level. Because Pb-210 dates were inconsistent with pollen dates, and because the pollen profiles could be interpreted in terms of dated vegetational changes, it was decided to reject the Pb-210 dates. A possible cause for the discrepancy between the pollen and Pb-210 dates is the erosion of bottom sediment. Because the lake is extremely shallow, bottom sediment can be eroded and exported from the lake during periods of high discharge of Stony Creek. Such erosional events appear to be reflected in the Pb-210 record, but may not be apparent from the pollen data (Robbins, 1978).

Magnetic susceptibility

Figure 6 shows the magnetic susceptibility profiles of nine cores spaced 100 m apart. Core 3 is located near the outflow end of the lake, whereas Core 19 is at the inflow. Indicated for each core is the boundary between the recent plant material and the black sediment (upper dashed line) and the boundary between the black sediment and the greyish brown sediment (lower dashed line).

In general, magnetic susceptibility is low in the greyish brown sediment at the base of the cores. Five cores show a sharp increase in magnetic susceptibility within the black sediment (Cores 3, 5, 7, 9 and 19). The remaining cores (11, 13, 15 and 17) show a smaller but noticeable increase in magnetic susceptibility towards the top of the core. In the upper part of the black sediment, all nine cores show a decrease in susceptibility to low values in the recent plant material.

Geochemistry

The description of the geochemical profiles is divided into two parts. The first part is concerned with the composition of the allogenic fraction, whereas the second part addresses the contribution of the authigenic and

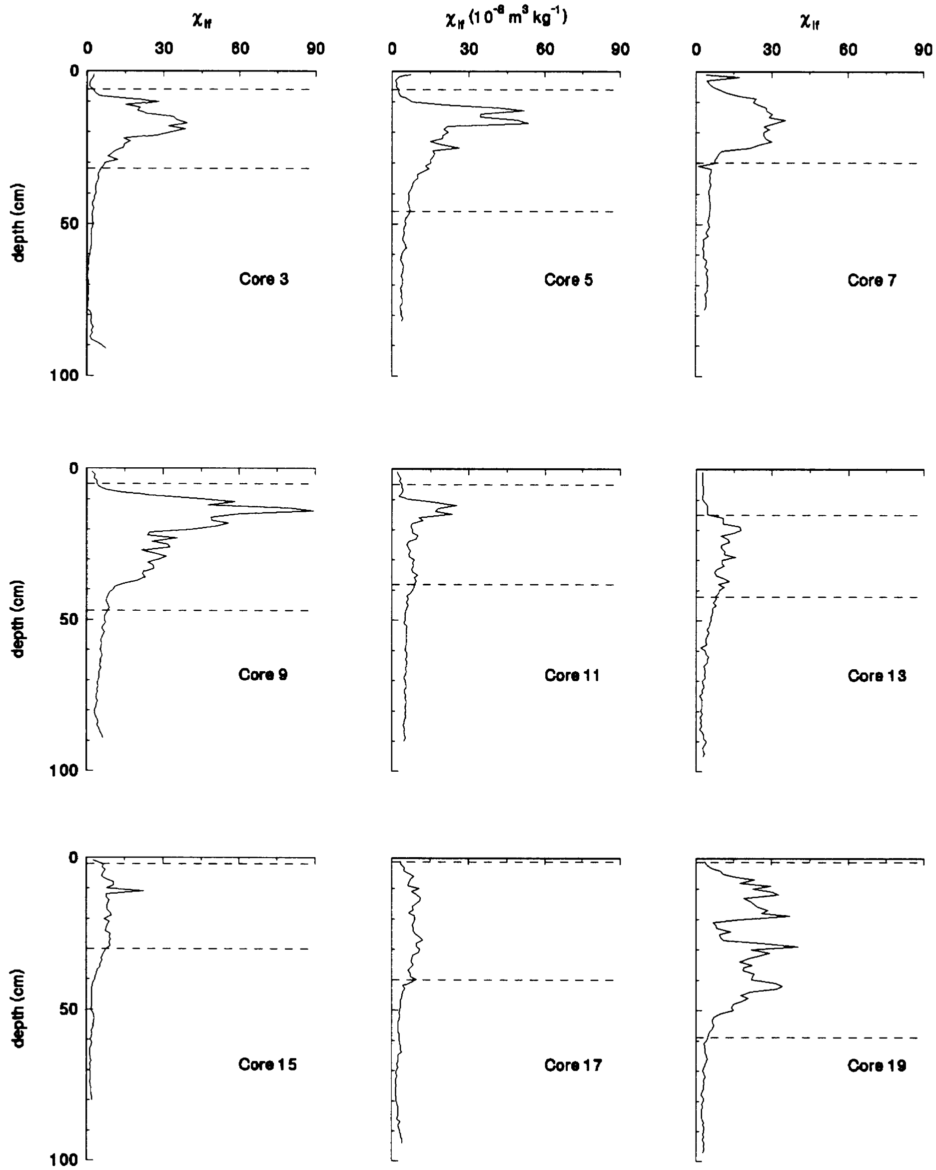

Figure 6. Magnetic susceptibility profiles of Stony Creek cores. For explanation of dashed lines, see Figure 5

allogenic fractions to the total chemical composition. It is worth noting that the bulk geochemical composition is, for the most part, controlled by the composition of the allogenic fraction. For brevity and clarity, elements having similar overall profile characteristics, geochemical behaviour and mineral associations were combined in groups. Each group was named after a typical element of that group. For consistency, all analysed elements were classified into groups even though some of the groups only contain one element.

Composition of the allogenic fraction. Figure 7 shows the composition of the allogenic fraction as geochemical profiles for selected elements. The elements were divided into five groups. The largest of these groups is the Al Group consisting of Al, K, Ti and Zr (Figure 7) and other metals such as Y and Sc (not shown) which have a similar profile. Elements of the Al Group have low concentrations in the greyish brown sediment at the base of the core, a sharp increase to peak values in the overlying black sediment, and a sharp decrease in

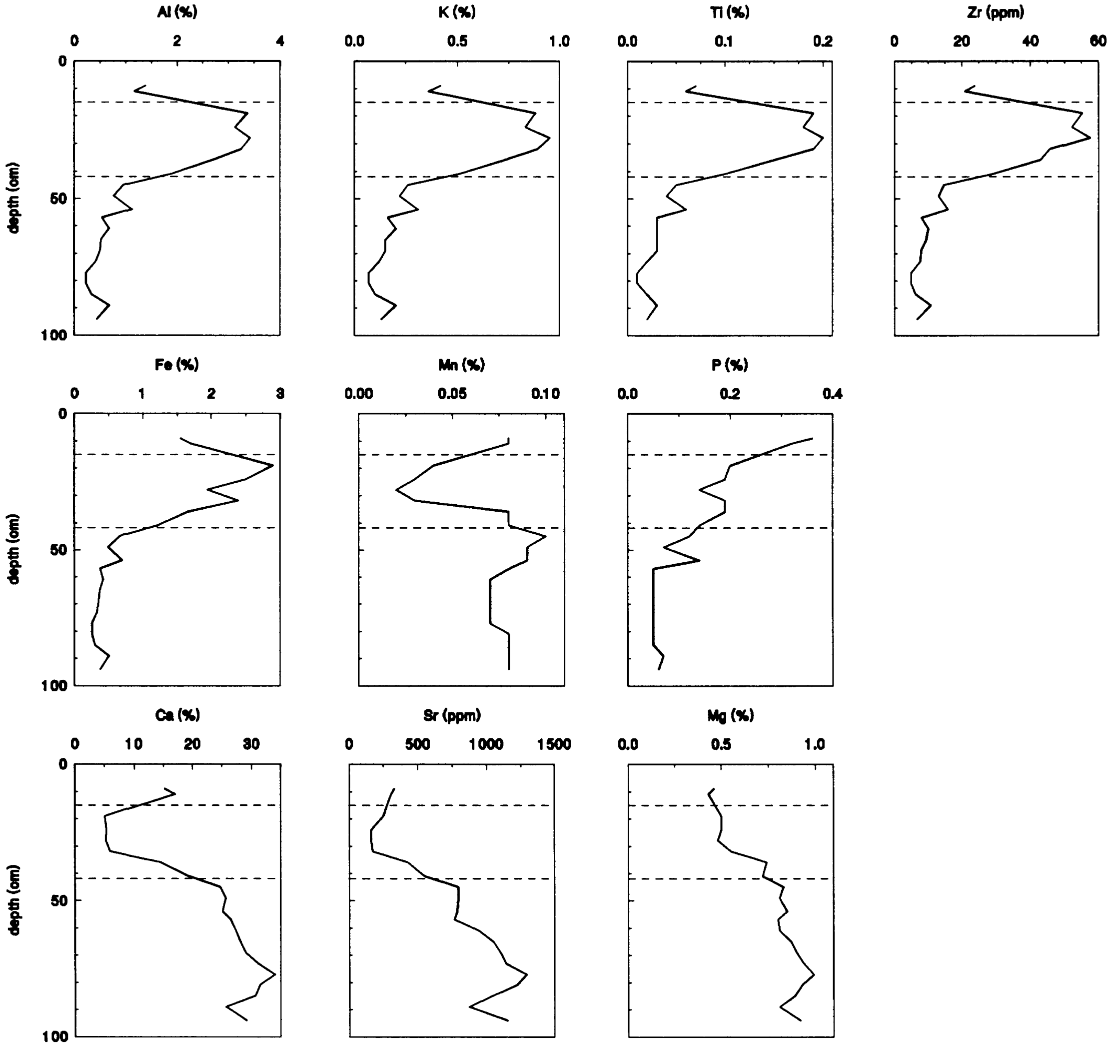

Figure 7. Selected geochemical profiles showing composition of the allogenic fraction of Stony Creek Core 13. For explanation of dashed lines, see Figure 5

the recent plant material at the top of the core (Figure 7). Elemental ratios within the Al Group show little variation with depth (Table I), indicating the strong association of the elements within this group.

The profile of Fe is very similar to those of the elements of the Al Group (Figure 7). Nevertheless, based on its geochemistry, especially its mobility under reducing conditions, Fe was classified by itself into a separate Fe Group. Similarly, the Mn Group consists of Mn by itself, based on its geochemical behaviour, which is similar to that of Fe, and on its distinct profile showing the highest concentration in the bottom part of the core, a sharp decrease in the overlying black sediment, and a marked increase in the upper layer of recent plant material (Figure 7). The P Group consists of P and As (not shown), both showing low values in the lower, greyish brown sediment followed by a gradually increasing concentration upcore. The Ca Group, containing the two elements Ca and Sr, has profiles which are markedly different from those of any of the other groups, in that the highest concentrations are found in the greyish brown sediment at the base of the core. Concentrations drop sharply in the overlying black sediments, and increase slightly in the recent plant material at the top of the core. The profile

Table I. Selected elemental ratios of the allogenic fraction

Depth (cm)	K/Zr	Ti/Zr	Y/Zr	K/Al
9	0·018	0·003	0·19	0·30
11	0·017	0·003	0·18	0·31
19	0·016	0·003	0·19	0·26
24	0·016	0·003	0·19	0·27
28	0·016	0·003	0·19	0·28
32	0·019	0·004	0·23	0·27
36	0·017	0·003	0·21	0·27
41	0·018	0·003	0·22	0·27
45	0·018	0·003	0·22	0·27
49	0·017	0·003	0·18	0·29
54	0·020	0·004	0·24	0·28
57	0·020	0·004	0·20	0·30
61	0·020	0·003	0·20	0·30
65	0·016	0·003	0·17	0·29
69	0·019	0·004	0·21	0·31
73	0·016	0·003	0·17	0·29
77	0·015	0·002	0·17	0·32
81	0·015	0·002	0·17	0·32
85	0·016	0·003	0·16	0·30
89	0·019	0·003	0·19	0·30
94	0·020	0·003	0·21	0·30

of the Mg Group, consisting of Mg, is similar to the profiles of Ca and Sr, except for a less pronounced decrease in concentration in the black sediment, and no significant increase within the recent plant material layer.

Contributions of the allogenic and authigenic fractions. The analysed elements were classified into five groups based on their contribution to the allogenic fraction. The same groups are evident from geochemical profiles showing the contributions of the authigenic and allogenic fractions to the total elemental concentrations in milligrams per gram dry sediment (Figure 8). The Al Group shows total concentrations which are low and show a slight increase upcore in the dark grey sediment at the base of the core. The transition to the overlying black sediment is marked by a sharp increase in total concentration to peak values reached between 20 and 35 cm. Total concentrations decrease again in the upper part of the black sediment and in the overlying plant material. At every depth, the allogenic fraction dominates the total concentration while the contribution of the authigenic fraction is insignificant. In contrast, all of the other groups do show a significant contribution of the authigenic fraction, at least at certain depths, if not throughout the core. The profile of total concentration of the Fe Group is very similar to that of the A1 Group (Figure 8). The contribution of the authigenic fraction, however, shows a sizeable peak between 20 and 30 cm depth in the black sediment. Profiles of the Mn Group contrast sharply with those of the Al and Fe Groups. Total Mn concentrations are relatively high in the greyish brown sediment of the lower part of the core, decrease sharply within the overlying black sediment to minimum values reached at about 30 cm depth, and increase again upward into the recent plant material (Figure 8). In the greyish brown sediment the allogenic fraction dominates the total Mn concentrations. Within the black sediment, however, the contribution of the allogenic fraction decreases sharply, whereas the contribution of the authigenic fraction shows a sharp increase. As a result, total Mn concentrations in the upper part of the black sediment are dominated by the authigenic contribution. In the upper part of the black sediment and into the recent plant material the allogenic contribution increases again whereas the authigenic contribution decreases. Profiles of the P Group show low total concentrations dominated by the allogenic contribution in the lower part of the greyish brown sediment. Total concentrations increase markedly between 50 and 60 cm depth, and from there upwards show a gradual increase. Within the black sediment, the authigenic contribution increases to a peak value reached at 30 cm, followed by a gradual decrease upcore. Total concentrations of the Ca Group showed the highest values in the greyish brown sediment in the lower part of the core. From there on, total concentrations generally showed a slight decrease upcore within the greyish brown sediment, followed by a sharp decrease in the black sediment to minimum values reached at about 30 cm. Above this depth, total

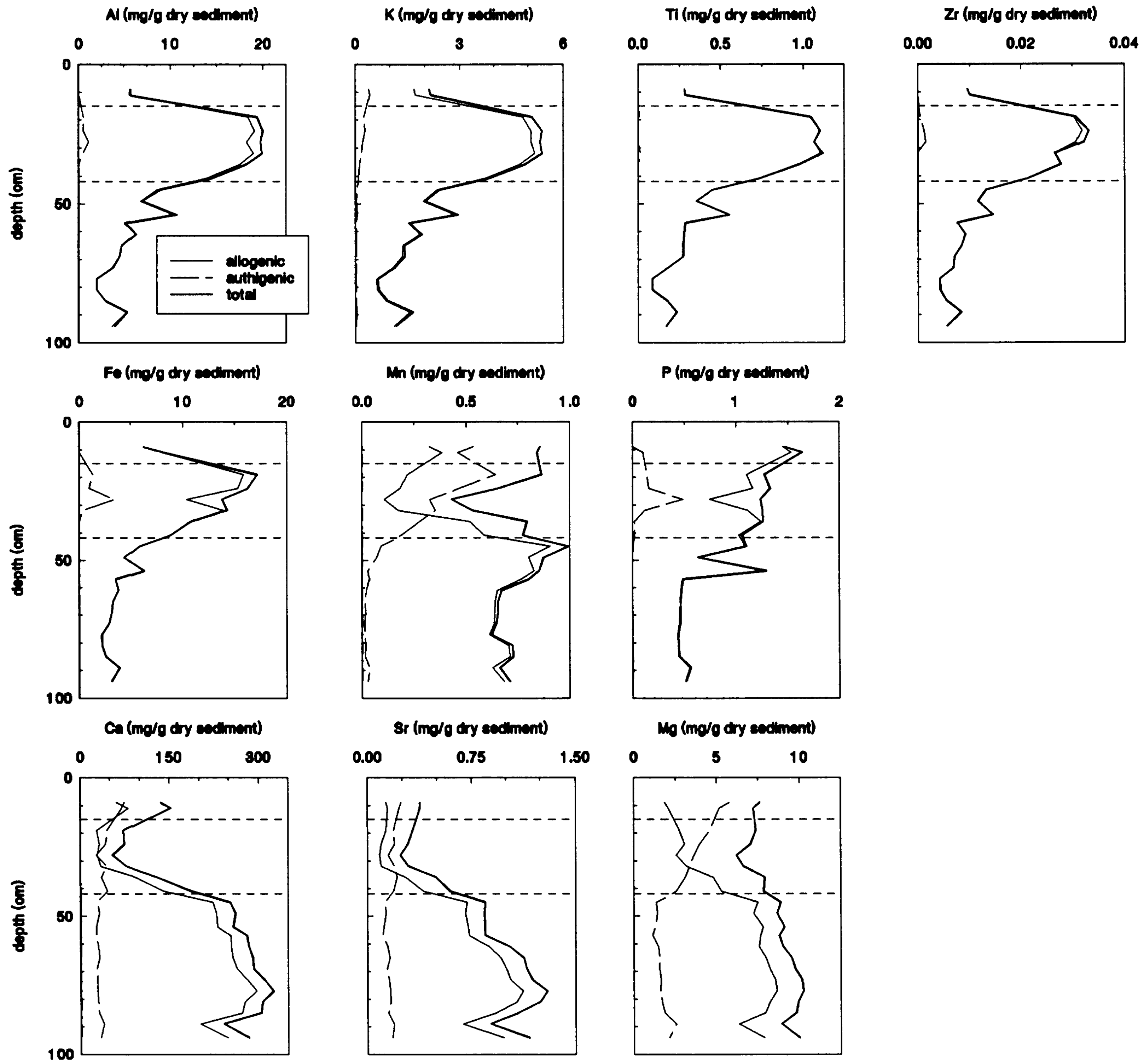

Figure 8. Selected geochemical profiles showing total concentrations and contributions of allogenic and authigenic fractions of Stony Creek Core 13. For explanation of dashed lines, see Figure 5

concentrations again increased gradually. For the Ca Group the contribution of the authigenic fraction was significant at all depths. The authigenic contribution was constant with depth within the greyish brown sediment, and increased slightly upward in the black sediment and the recent plant material. Profiles of the Mg Group show a less pronounced decrease in total concentration in the black sediment, even though the allogenic contribution decreases markedly upward of the lower boundary of the black sediment. The decrease in the allogenic contribution, however, is negated by the authigenic contribution, which increases towards the top of the core.

Overall, the geochemical profiles in Figure 8 show that even though the allogenic fraction dominates lake sediment chemistry for some elements, this is not true for others such as Mn, Ca, Mg and Sr. Consequently, assessing the contributions of various sediment fractions becomes crucial for interpreting the lake sediment record in terms of erosional history.

DISCUSSION

Dating

In Core 13 a distinct boundary at 42 cm separates the greyish brown sediment from the overlying black sediment (Figure 3). This boundary is also evident from the profiles of LOI (Figure 3), magnetic susceptibility (Figure 6) and geochemistry (Figures 7 and 8). In the pollen diagrams (Figure 4) the 42 cm boundary corresponds to a marked increase in the percentage of *Populus* pollen. Based on the vegetational history of the region, this increase in *Populus* pollen is interpreted as indicating the start of agricultural settlement which resulted in the suppression of natural and man-made fires in the region. The interpretation of the 42 cm boundary as the agricultural settlement boundary implies a date for that boundary in the 1880s to 1900s, depending on how rapidly settlement would have had a noticeable impact on the vegetation cover.

Further dates are obtained from the Cs-137 profile. The standard interpretation of Cs-137 profiles is that the first rise in activity corresponds to 1954 whereas the peak indicates 1963. The interpretation of Cs-137 profiles, however, is complicated by sediment mixing, diffusion of Cs-137 under reduced conditions, and the influx of topsoil with high Cs-137 concentration. A number of studies have compared Cs-137 dates to other, independent methods of dating, and found that Cs-137 tends to indicate dates which are too young, suggesting a downward flux of Cs-137 after deposition (e.g. Robbins *et al*., 1978; Oldfield *et al*., 1978; Foster *et al*., 1985). If it is assumed that these effects can be ignored, the Cs-137 profile provides dates of 1963 at 7 cm depth and 1954 at 21 cm depth, where 21 cm is midway between 17 and 25 cm.

Geochemistry and magnetic susceptibility

The changes in sediment colour, LOI and palynology at the 42 cm agricultural settlement boundary coincide with distinctive changes in sediment geochemistry (Figures 7 and 8). Below the settlement boundary, the geochemistry of the allogenic fraction shows high concentrations of the Ca and Mg Groups and low concentrations for all other groups. At the settlement boundary, the allogenic fraction shows a sharp increase in the Al, Fe and P Groups, and an equally sharp decrease in the Ca and Mg Groups. This change in geochemistry is interpreted as indicating that settlement and the associated change in land use from prairie grassland to farmland resulted in a greater contribution of topsoil to the sediment load in the contributing basin. This interpretation is supported by data on the mineralogical differences between the sola and parent materials for chernozemic and luvisolic soils in Saskatchewan. During soil formation, calcite and dolomite are the first minerals to disappear from the A and B horizons, and total losses of Ca, Na and K feldspars range from 10 to 40 per cent (St. Arnaud and Sudom, 1981). In addition, Zr is typically enriched in the silt fractions of the A and B horizons (Sudom and St. Arnaud, 1971) and the highest concentrations of Fe occur in the B horizon (St. Arnaud and Whiteside, 1964).

Within the Al Group, elemental ratios are close to constant throughout the core as shown, for example, by the K/Zr, Ti/Zr, Y/Zr and K/Al ratios in Table I. These four ratios are interpreted as being characteristic for an allogenic sediment source, specifically topsoil, which has contributed to the allogenic fraction both prior to and after settlement, but which has a much larger contribution during the post-settlement period.

The interpretation of the geochemical profiles as indicating increased topsoil erosion following settlement is consistent with the magnetic susceptibility profiles. In Core 13, the settlement boundary at 42 cm is associated with a noticeable increase in magnetic susceptibility. Thompson and Oldfield (1986) discussed similar profiles and concluded that in the majority of cases the susceptibility increases can be interpreted as an increased input of allogenic magnetic minerals. Such minerals are formed during weathering and soil formation from the iron-bearing minerals in bedrock, resulting in an increased magnetic susceptibility of the topsoil relative to the underlying soil horizons and sediments. A number of studies have used this contrast in magnetic properties to evaluate the contribution of topsoil to the suspended load of a stream (e.g. Oldfield *et al*., 1979; Walling *et al*., 1979). Nestor (1996) investigated the magnetic susceptibility profiles of chernozemic black soils of the Oxbow Association and found that the susceptibility of the A and B horizons exceeded that of the parent material.

Table II. Temporal variability of deposition rates of total sediment, the allogenic fraction, and selected elements in the allogenic fraction for Core 13

	1900–1954	1954–1963		1963–1992	
	Rate ($mg\,cm^{-2}\,a^{-1}$)	Rate ($mg\,cm^{-2}\,a^{-1}$)	Change*	Rate ($mg\,cm^{-2}\,a^{-1}$)	Change
Estimates based on 1963 Cs-137 peak at 7 cm depth					
all fractions	206	611	2·96	70	0·11
allogenic fraction	126	314	2·50	31	0·10
Al	3·71	6·25	1·68	0·39	0·06
K	1·00	1·77	1·77	0·12	0·07
Ti	0·21	0·34	1·62	0·02	0·06
Zr	0·006	0·010	1·75	0·001	0·07
Fe	2·63	5·72	2·17	0·50	0·09
Mn	0·06	0·21	3·51	0·02	0·12
P	0·22	0·84	3·84	0·10	0·12
Ca	11·6	41·2	3·56	4·97	0·12
Mg	0·73	1·58	2·16	0·14	0·09
Sr	0·036	0·095	2·64	0·010	0·10
Alternative estimates based on 1963 Cs-137 peak at 13 cm depth					
All fractions	206	349	1·69	130	0·37
Allogenic fraction	126	179	1·43	57	0·32

* Factor by which the deposition rate changed relative to the previous period

The decrease in magnetic susceptibility near the top of the core can be attributed to a decrease in topsoil contribution, dilution of the magnetic minerals with organic materials, or a combination of both. It is likely that the magnetic susceptility decrease is at least partly caused by a decreased topsoil contribution because the susceptibility decrease coincides with a change in the geochemistry of the allogenic fraction.

Based on the geochemical profiles, the predominant pre-settlement sediment source for the allogenic fraction was likely to be the carbonate-rich till exposed in the stream banks and bed. Preliminary X-ray diffraction (XRD) data show that the dominant minerals in bulk sediment samples (i.e. with no separation of the various fractions) were (in order of importance) calcite, quartz and aragonite in the brownish grey pre-settlement layer, and quartz and calcite in the black post-settlement layer.

The change in composition of the allogenic fraction as a result of changing sediment sources upon agricultural settlement is quite distinct from the findings reported in the admittedly small number of other studies. Engstrom *et al*. (1985) investigated the geochemistry of a lake core in Vermont covering a record from 1000 years BP to the present, and found that the elemental composition of the allogenic fraction was virtually constant throughout the core, despite major changes in land use, vegetation cover and erosion rates. Similar findings were reported by Engstrom and Hansen (1985) for a lake sediment record of 10 500 years from Labrador.

Post-settlement deposition rates

Deposition rates for Core 13 can be calculated for three post-settlement periods from dry bulk densities and dates derived from the pollen and Cs-137 profiles. Table II shows the change in deposition rates for the total sediment (i.e. all fractions), the allogenic fraction and selected elements within the allogenic fraction. Also shown is the factor by which each deposition rate changed relative to the previous period.

Deposition rates increased sharply between the periods 1900–1954 and 1954–1963, and decreased again during 1963–1992 to levels below those for 1900–1954 (Table II). Two factors, annual precipitation and land use, were investigated to explain the temporal pattern of deposition rates. Figure 9 shows that the 1954–1963 period was characterized by a variable annual precipitation at Kamsack and Yorkton. Examination of monthly records indicates that high annual precipitation values primarily result from high rainfalls in June and July which, because of convectional activity, are normally the wettest months of the year. Conversely, low annual precipitation values are typically caused by a scarcity of summer precipitation. Because the annual precipitation for 1954–1963 is similar to that for 1963–1992, precipitation cannot be used to explain the contrasting deposition rates between these two periods. Historical changes in land use, however, partly explain

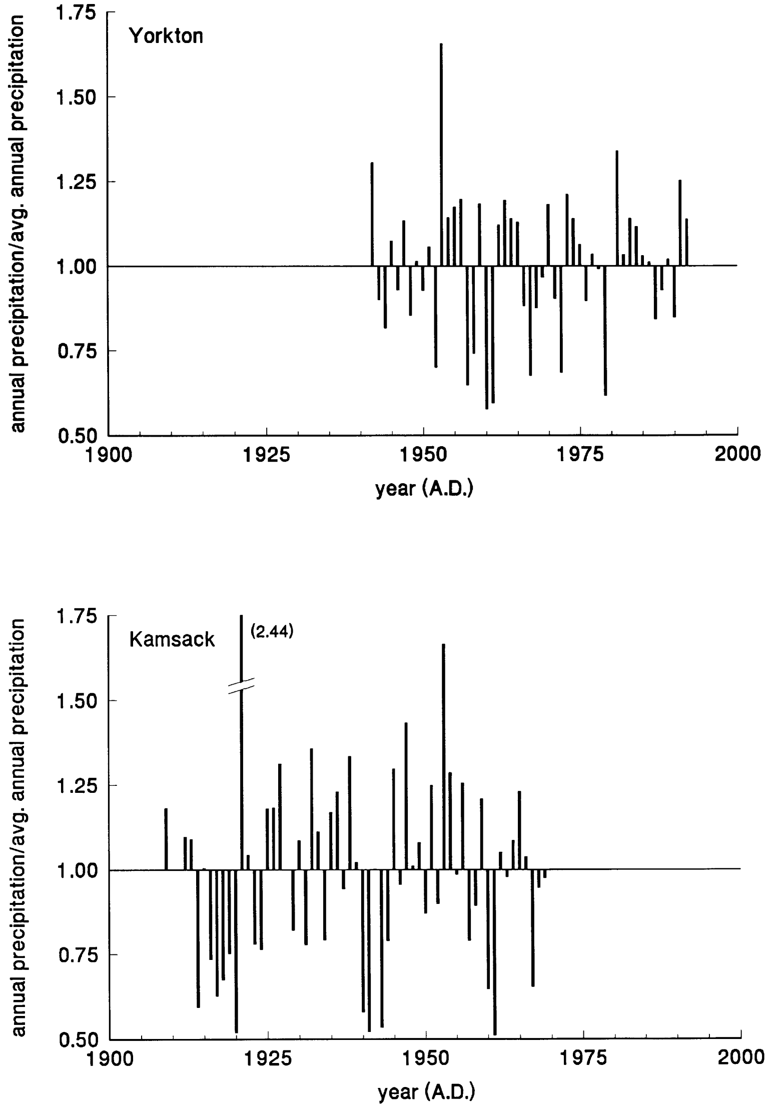

Figure 9. Ratio of annual precipitation to average annual precipitation for Yorkton and Kamsack.

the variation in deposition rate. From 1940 to the present the area under field crops has sharply increased (Figure 2). Using the area under field crops as a surrogate index for the area affected by accelerated soil erosion, the high deposition rates during 1954–1963 can be explained by this expansion. Following this reasoning, deposition rates during the previous period (1900–1954) are likely to have been lower because the area under field crops was small (<30 per cent) and remained almost constant prior to 1940. Because the deposition rate is calculated as an average for 1900–1954, the expected increase in deposition rates associated with expansion of the area under field crops after 1940 is not evident.

The low sedimentation rates for the most recent period (1963–1992) cannot be explained by precipitation, which was variable over this timespan, or by the area under field crops, which continued to increase. The effect of an increase in the area under field crops on soil erosion and lake sedimentation during this period is likely to have been negated by the poorly integrated drainage network in the hummocky terrain. Numerous closed depressions lead to a large difference between the gross and net drainage areas for Stony Creek. As a result, the area under field crops may be an index of the area undergoing accelerated soil erosion, but is not necessarily an

accurate measure of the area contributing sediment to the stream. Furthermore, sediment conveyance is discontinuous because of the numerous sediment traps along the drainage network (e.g. beaver ponds). The most likely explanation for the decrease in sedimentation rates is that an increased application of soil conservation practices reduced soil erosion rates. For example, ploughing traditionally was used to control weeds during summer fallow. During wet years it was necessary to plough fallow fields a number of times, resulting in a significant exposure of bare soil during the summer rainfall season and high soil erosion rates. The current widespread use of herbicides to control weeds during summer fallow would result in a reduction in soil erosion rates, for instance, because of the presence of a protective layer of plant material on the surface and because of the formation of a resistant surface crust.

A comparison of the factors by which deposition rates changed in relation to the previous period clearly shows that different sediment fractions and groups of elements behave very differently (Table II). The contribution of the allogenic fraction to total sediment deposition decreased, from 61 per cent in 1900–1954, to 51 per cent in 1954–1963, to 44 per cent in 1963–1992, whereas the contributions of the authigenic and biogenic fractions increased. More important for the purpose of this paper, however, is the different behaviour shown by the various elemental groups within the allogenic fraction (Table II). The elements of the Al Group (e.g. Al, K, Ti and Zr in Table II) all change by the same factor from period to period, again indicating the presence of a sediment source characterized by specific ratios of these elements (Table I). The factors in Table II indicate that the contribution of this source to the allogenic fraction has decreased from 1900 to the present. For example, the deposition rate for the allogenic fraction increased by a factor of 2·50 from 1900–1954 to 1954–1963. Over the same time span, the deposition rates for the Al Group elements increased by an average factor of only 1·71. In contrast, the increase from 1900–1954 to 1954–1963 in the deposition rates of Mn, P and Ca exceeded the increase of the allogenic deposition rate. The shifts in the contributions of various sediment sources from 1900–1954 to 1954–1963 continue from 1954–1963 to 1963–1992. Table II shows that from 1954–1963 to 1963–1992 the deposition rates of the Al Group decreased more than the deposition rate of the allogenic fraction, whereas the deposition rates of Mn, P and Ca decreased less than the deposition rate of the allogenic fraction.

In summary, differences in the rates of change of deposition rates of the various elemental groups within the allogenic fraction indicate a shift in sediment source contributions during the post-settlement period. A comparison of the allogenic deposition rates for the three post-settlement periods indicates a decrease in the contribution of a sediment source characterized by specific ratios for the Al Group elements, and an increase in the contribution of a sediment sources characterized by increased percentages of Mn, P and Ca. It should be noted that this pattern, indicated by deposition rates for the allogenic fraction (Table II),confirms that shown by the elemental profiles for the allogenic fraction (Figure 7). The post-settlement change in composition and deposition rates for the allogenic fraction is interpreted as a decrease in the contribution of topsoil. This interpretation is consistent with the magnetic susceptibility profiles, which all show a decrease in susceptibility towards the top of the core (Figure 6).

Any interpretation of the deposition rates should recognize the limits of the temporal resolution provided by the three dates for Core 13. Thus, high sedimentation rates for 1954–1963 are likely to reflect an increase in sedimentation rates which started prior to 1954 and continued past 1963. Indeed, between 1954 (at 21 cm) and 1963 (at 7 cm) the topsoil contribution decreased, as shown by magnetic susceptibility (Figure 6) and allogenic geochemistry (Figure 7). Hence, sedimentation rates for a period of unknown length prior to 1954 are likely to have been higher than those estimated for the 1954–1963 period but, because the sedimentation rate is averaged from 1900 to 1954, high rates before 1954 are not evident. Furthermore, estimated deposition rates for the 1954–1963 and 1963–1992 periods depend on the precise depth of the 1963 Cs-137 peak. Available Cs-137 data suggest that the 1963 peak lies at 7 cm depth. The limited resolution of the Cs-137 data, however, means that the actual peak could lie between 7 and 13 cm depth. To evaluate the effect of this uncertainty, alternative deposition rates were calculated using a depth of 13 cm for the 1963 Cs-137 peak (Table II). The effect of lowering the depth of the 1963 Cs-137 peak is to decrease the deposition rate for the 1954–1963 period, and to increase the deposition rate for 1963–1992. Nevertheless, the alternative estimates of the deposition rates for the three periods show the same temporal pattern as the original estimates, i.e. an increase between the periods 1900–1954 and 1954–1963, followed by a decrease during 1963–1992, even though the changes in deposition rate from one period to the next are less dramatic than in the original estimates (Table II).

CONCLUSIONS

The impact of European settlement in North America on the suspended load of streams has been investigated in a number of locations. The majority of these studies focused on sediment quantity, and dealt with the effect of settlement on the magnitude of the suspended load. Relatively few studies have considered sediment quality. Lake sediment geochemistry in the Stony Creek basin indicates that, following European settlement, the balance between the various sediment sources in the contributing basin changed, owing to the increased contribution of farmland topsoil.

The following points summarize the findings of this study.

1. Settlement in the field area led to a dramatic change in the geochemistry of the allogenic fraction (Figure 7). This change is interpreted as reflecting a greater contribution of farmland topsoil to the sediment load of the contributing basin. This interpretation is consistent with the magnetic susceptibility profiles, which show a marked increase at the settlement boundary (Figure 6).
2. Elemental ratios of Al, K, Ti and Zr do not vary significantly throughout the core (Table I). This lack of variation is interpreted as indicating the presence of a sediment source in the contributing basin with characteristic elemental ratios for these elements. Based on the geochemistry of the allogenic fraction, this sediment source is most likely to be topsoil. Hence, prior to settlement, topsoil erosion did contribute to the allogenic fraction, although not to the same extent as during the post-settlement period.
3. Following settlement, changes in geochemistry and deposition rates of the allogenic fraction occur in response to changes in land use. Deposition rates for 1954–1963 are significantly higher than during the preceding (1900–1954) and subsequent (1963–1992) periods. The high deposition rates for 1954–1963 probably reflect a period of high topsoil contributions which started prior to 1954. The decrease in deposition rates during the most recent period reflects a more widespread application of soil conservation measures. This interpretation is consistent with the decrease in topsoil contribution indicated by changes in the deposition rates for individual elements within the allogenic fraction (Table II), and with a decrease in magnetic susceptibility towards the top of the core (Figure 6).
4. During the post-settlement period, the factors by which deposition rates of individual elemental groups within the allogenic fraction have changed are different for the various groups (Table II). This variability is interpreted as indicating that different sediment sources in the basin respond in different ways to changes in land use. At present, research is in progress to identify further these sources.
5. During the post-settlement period, the erosional response of the drainage basin appears to be controlled by land use rather than by climatic factors such as annual precipitation. The dominance of land use as a driving factor reflects the dramatic changes that the North American landscape has undergone since European settlement. It calls for a greater effort to investigate the balance between land use change and climatic change as controls of future landscape response.

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